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Comparison of Gold/Platinum and Gold/Ruthenium Contacts on Piezoelectrically Actuated RF MEMS Switches

by Robert Proie, Daniel Judy, Ronald G. Polcawich, and Jeffrey Pulskamp

ARL-TR-5218 **June 2010**

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14. ABSTRACT
Lead zirconate titanite (PZT) radio frequency (RF) microelectromechanical system (MEMS) switches developed at the U.S. Army Research Laboratory (ARL) were fabricated with half of the switches on each wafer—approximately 30 switches—using the typical gold/platinum contacts and using gold (Au)/ruthenium (Ru) contacts for the other half. We measured several important parameters using an Electroglass automated probe station, including contact resistance, actuatoion voltage, and bias current. The switches were cycled a number of times and the measurements were repeated. In addition, samples of five switches of each type were cycled to failure, and the mean output voltage was logged to assess the effect of these contact materials on the lifetime.

15. SUBJECT TERMS
RF MEMS, contact metallurgy, piezoelectric

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1. Introduction/Background

Ever since Richard Feynman piqued the interest of researchers with his talk, *There's Plenty of Room at the Bottom*, there has been a considerable amount of work done in the field of miniaturized devices. Due to the increased precision of device fabrication techniques, partially driven by the large commercial demand for faster and lower power silicon microprocessors, researchers have the ability to design and fabricate devices on the micro- and nano-scales (*1*). In recent years, research regarding these devices, referred to as micro-electro-mechanical systems (MEMS), has become increasingly popular.

The concept of radio frequency (RF) MEMS switches is a specific area that shows a great deal of promise. Recently, researchers have demonstrated a number of advantages that RF MEMS switches have over the popular alternatives, specifically PiN diodes and field effect transistors (FET). These advantages include high isolation, low insertion loss, and very low power consumption (*2*). In addition, these switches have shown near linear operation over the intended range of use, from near DC to 50 GHz. This results in a reduction of spurious products during switching, which loosens the constraints imposed on other components within the RF system.

In addition to the general attention of RF MEMS switches within high frequency systems, the defense arena has shown a considerable amount of interest in producing phased array antennas for both communication and radar systems (*3*). In reference 4, a Ku-Band, 3-bit phase shifter was demonstrated with a maximum insertion loss of 1.23 dB/bit, compared to the 1.6 dB/bit insertion loss achieved by a gallium arsenide (GaAs)-FET design (*2*).

Despite these advantages, several hurdles remain before wide-scale adoption takes place. One of the primary hurdles is integration. Use of the popular RF-enabling fabrication technologies, such as bipolar junction transistor enabled complimentary metal oxide semiconductor technologies (BiCMOS), RF-CMOS, and silicon-germanium (SiGe), allows digital CMOS circuitry to be fabricated on the same die as the high frequency components. Most MEMS technologies, however, have not maturated to the point of a process marriage at that level. This results in a large, more complicated, and more costly system, with an increased potential for failure. Motivated by that issue, the groundwork has begun to design a CMOS alternative for RF MEMS switch systems, as shown in (*4*).

The other, more detrimental hurdle results from the reliability of these devices. Numerous techniques have been experimented with in order to achieve the high (over 20 billion-cycle) reliability required by a defense or commercial product. The remainder of this report will examine piezoelectrically actuated RF MEMS switches, and a potential improvement in reliability through contract resistance improvement.

The MEMS devices we tested (see figure 1) used the inverse piezoelectric effect to produce the mechanical motion that opened and closed the switch. The inverse piezoelectric effect occurs when an applied electric field induces mechanical motion.

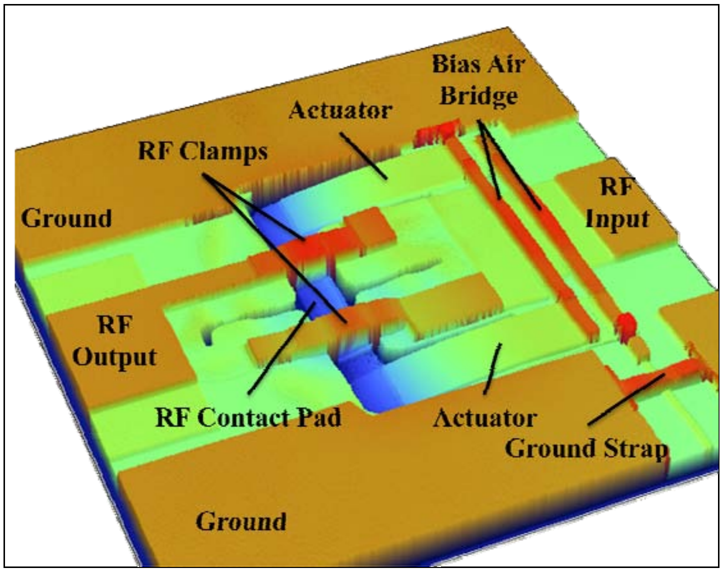

Figure 1. Optical profilometer image illustrating the primary components of the tested PZT switches.

In this specific situation, the switch uses two arms/actuators created from a platinum-PZT-platinum sandwich and a lower structural layer. An electric field is produced by grounding one of the platinum electrodes and supplying a bias potential to the other electrode. Upon generation of that electric field, the piezoelectric material in the middle, PZT, experiences a compressive strain that produces a moment about the neutral axis of the structure, causing it to deflect. With proper design of the actuator structure and location of the neutral axis, the cantilever can be made to bend up, raising the RF contact pad, which forms the electrical connection between the RF input and output lines.

It is in that contact point that this report is concerned. Specifically, the contact materials are altered from a gold (Au)/platinum (Pt) combination to a Au/ruthenium (Ru) combination. It is theorized that this change will lead to a much more gradual increase in contact resistance over the lifetime of the device.

A testing procedure is established to verify objectively the performance of each device and the criterion for a malfunctioning device in section 2. Section 3 provides and discusses the results measured during those tests. Section 4 summarizes those results and draws a conclusion regarding the effectiveness of Au/Ru contacts versus Au/Pt contacts.

2. Experimental Procedure

This study focused on one specific switch design (see figure 2). This switch varies from the version presented in (*5*) because of the two clamped-clamped strips that are anchored above and perpendicular to the movable RF contact pad. We chose this switch over the switch described in (*5*) because it is generally less susceptible to bending during the top metal liftoff process step than is the dual cantilever structure. It may also reduce switch bounce and, thus, have a direct impact on switch contact lifetime.

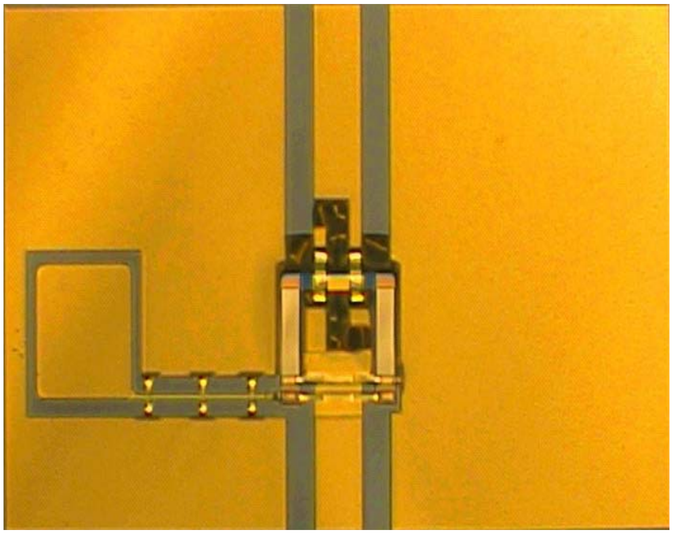

Figure 2. An optical image of the PZT switch tested. This switch is characterized by two overhanging clamps that are bridged by the RF contact pad when the device closes.

The device testing was broken into two stages. In stage one—the preparation stage—device functionality was examined. Since this study's purpose was to examine the impact of only the contact material on device lifetime, it was important to eliminate devices that showed other, unrelated issues. While we had already laid the groundwork for stage, a portion of this study was intended to standardize the procedure for future testing.

All preparation steps were performed on a sample of 13 devices, with contact resistances and poling voltages recorded during each step. The preparation effectiveness was then examined in order to determine if any changes were necessary before stage two, the lifetime testing.

The preparation stage testing setup (figure 3) required several pieces of equipment. A DC source, connected to the device under test via two DC probes, supplied the actuation voltage. The testing procedure required actuation voltages from 0 V to 25 V. Either a network analyzer with a bias-t connection (shown) or semiconductor parameter analyzer produced the signal down the RF path by way of two RF probes.

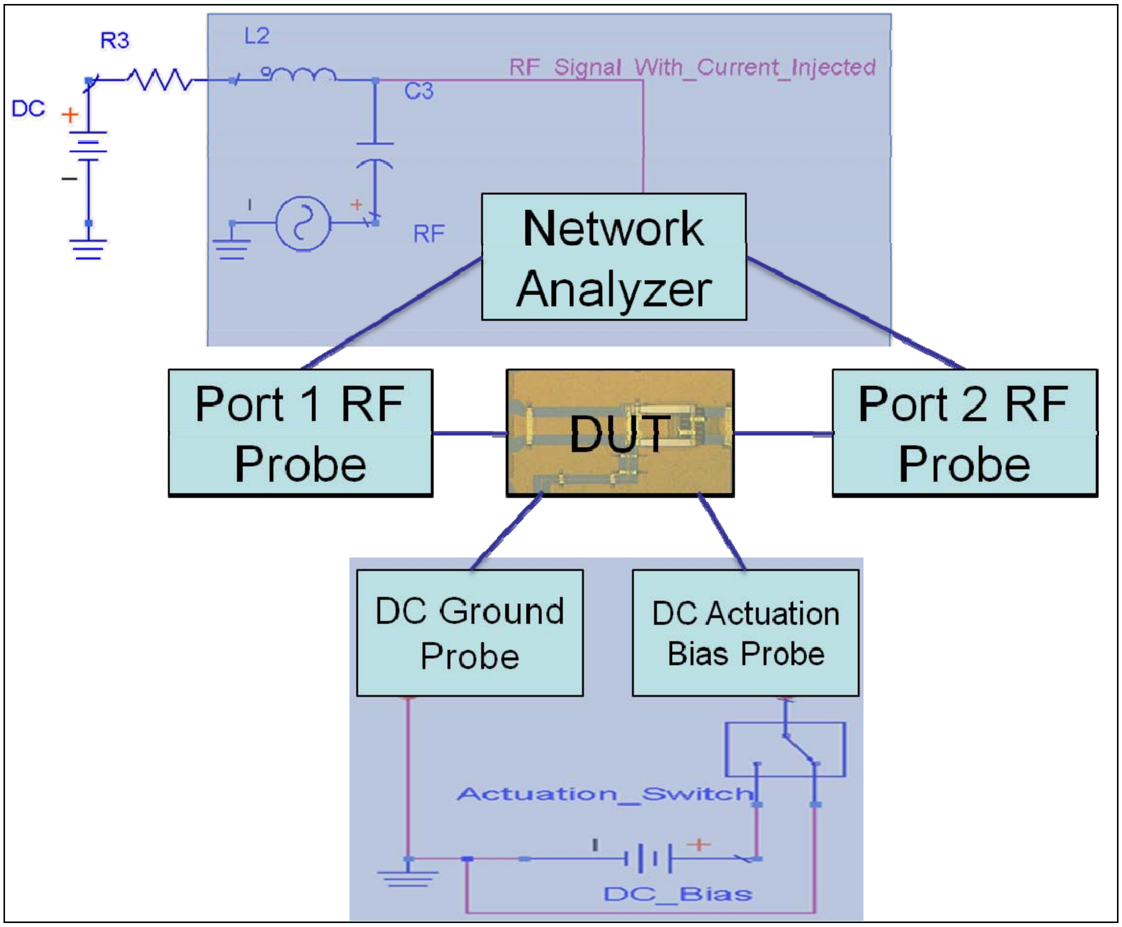

Figure 3. The test setup for the preparation phase of testing.

The preparation stage was broken into three steps. The first step involved poling each device for 1 min. It has been shown that poling piezoelectric ceramic materials, specifically PZT in (*6*), with a strong electric field effectively aligns the domains in the direction of the field. The electric field was produced by a 20 V potential difference between the two electrodes. This, in turn, results in increased mechanical deflection at a given bias voltage. This poling voltage was applied for 1 min and the switch was then toggled.

Following device-poling, we used current conditioning to improve the contact resistance of each device. As indicated by (*7*), currents as high as 100 mA have been shown to break up contamination on electrical contacts, thus providing reduced contract resistance. In these devices, the RF line provided a direct electrical path to the contact. In order to apply current along the RF line, a bias-t setup (see figure 3) was first connected; the DC source used in that configuration supplied 2 V with a maximum current of 75 mA. Then, the actuation voltage was swept from 0 V to 25 V. The current was limited to 75 mA in order to avoid damaging the contacts.

The final preparation step was to measure the device's new minimum actuation voltage and contact resistance. These measurements were taken with 0 V DC supplied to the bias-t. At this point, devices were binned into one of four categories: no electrical contact (stuck open), shorted (stuck closed), contact resistance below 5 Ω, and contact resistance greater than 5 Ω. We only used devices with a contact resistance below 5 Ω for the second stage of testing.

After verification of the testing preparation stage, an electroglass probe station was used to automate the process. In that setup, the network analyzer and DC power supply were replaced by a semiconductor parameter analyzer. A computer was used to control the probe station and record the data obtained by the parameter analyzer.

The second stage of testing, termed lifetime testing, involved cycling the switch until failure. A failed switch was defined as a switch where the average voltage dropped below 50% of the expected average for more than 10 samples.

The setup (figure 4) required multiple pieces of testing equipment. First, we used a function generator and amplifier sequence to supply the actuation voltage—a 15 Vpp square wave at 1000 cycles per second with a 50% duty cycle. Another function generator supplied a voltage along the RF path. Two square wave pulses were supplied per actuation pulse. The first pulse occurred sufficiently after the visible switch bounce subsided and lasted for 0.25 ms. The second pulse occurred after the removal of the actuation voltage and lasted for 0.25 ms. We used this technique, called cold switching, to avoid electrical arcs that could occur during state transitions.

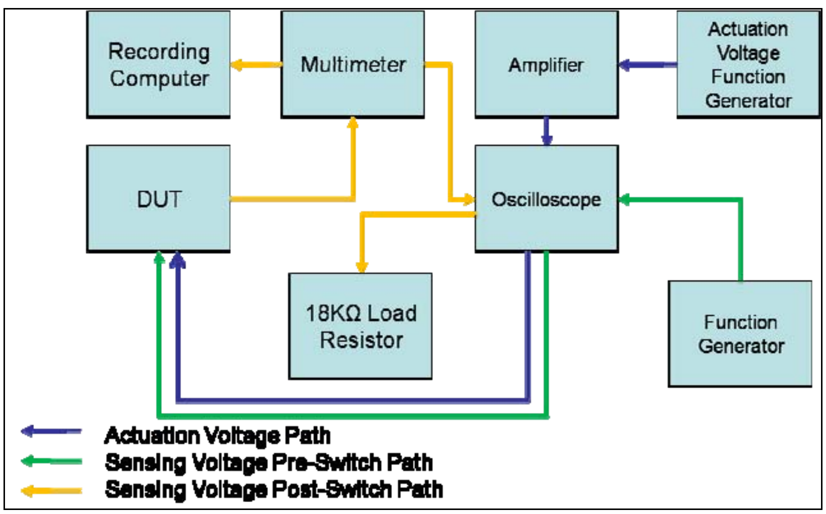

Figure 4. The lifetime testing setup used in the study.

In addition to the function generators, a multimeter and an 18 KΩ load resistor were placed in series with the switcher's output. The multimeter was used to read the mean voltage output from the switch, and an attached computer recorded that value once every second. Finally, an oscilloscope was used to allow visual verification of correct operation for each of the signals. This setup was used to record the lifetime of 10 Pt/Au contact switches and 10 Ru/Au switches.

3. Results and Discussion

As mentioned previously, the first step of the preparation stage was to pole the devices for 1 min. Figure 5 shows a comparison between the actuation voltage required before poling and afterwards. As is shown, before poling occurred, a majority of the devices required an actuation voltage greater than 12 V. After poling, all of the devices were successfully actuated under 8 V.

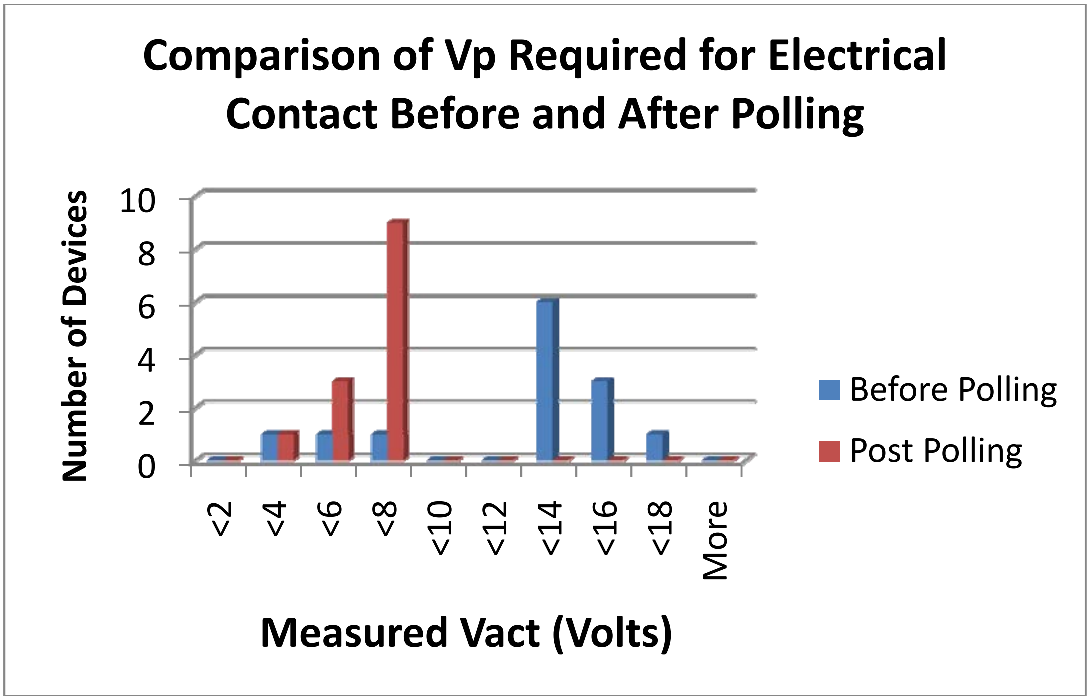

Figure 5. The activation voltage required to make electrical contact before and after device poling.

Step 2 of the preparation stage was current conditioning. The pre-conditioning and post-conditioning contact resistances are presented in figure 6. Before this step, a majority of the devices had a contact resistance over 200 Ω and some were over 1 KΩ. After conditioning, the contact resistance of each device was under 5 Ω.

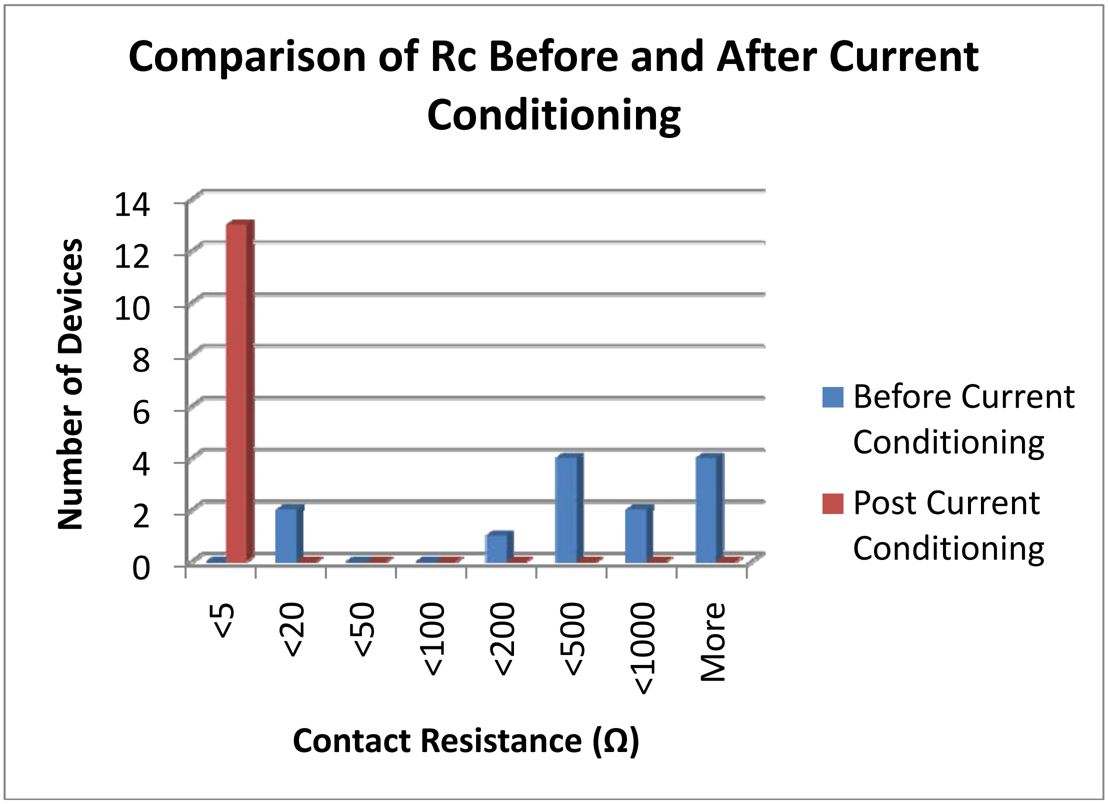

Figure 6. The contact resistance observed before and after device current conditioning.

The results we obtained were sufficient to provide confidence in the preparation method. Following that verification, the automated preparation system aforementioned was used to examine a complete wafer composed of half Au/Ru devices and half Au/Pt devices. Table 1 shows a summary of these results.

Table 1. A summary of the data recorded throughout the testing process.

	Platinum/Gold	**Ruthenium/Gold**
Initial Conditions		
• Average Vact	15.33 V	17.32 V
• Average Rc	2518.90 Ω	14285.14 Ω
• Working Devices	21	19
Post-Preparation Conditions		
• Average Vact	7.52 V	9.29 V
• Average Rc	9.61 Ω	14.45 Ω
• Working Devices	21	24
Lifetime		
• Average Lifetime	2.2 Million Cycles	6.2 Million Cycles
• Minimum Lifetime	37,000 Cycles	29,000 Cycles
• Maximum Lifetime	10 Million cycles	33 Million Cycles

The wafer contained 31 Au/Pt devices and 28 Au/Ru devices. The average Vact is the average actuation voltage required to achieve electrical contact, and the average Rc was the contact resistance recorded for the device. Both numbers only take into account those devices that achieved electrical contact without being stuck closed.

For both types of contacts, the actuation voltage required after preparation was approximately half of the initial Vact. The contact resistance also decreased substantially. Note that the Rc shown includes the resistance of the cables used to take the measurements.

One point of interest is that five Au/Ru devices were unable to make electrical contact initially due to a combination of a high Rc and Vact. After conditioning, these devices were able to function at a much more acceptable level.

The final row in table 1 shows the lifetime results obtained for a sample of 20 devices—10 Au/Pt devices and 10 Au/Ru devices. Devices with Ru contact material lasted approximately three times longer than the Pt version. In both situations, several devices failed relatively quickly. Of the top six performing devices, four of them used the Ru/Au contact combination, including the best performing device.

4. Conclusion

This study has shown the validity of a method that objectively prepares and separates functional devices from those that are not working as intended. In addition, the contact material combination of Au/Ru was shown to produce devices that lasted three times longer than the Au/Pt alternative.

Throughout the course of this study, humidity was observed to negatively impact the lifetime of these devices. For several days, the humidity was over 50% within the laboratory due to a malfunctioning air conditioner. Measurements taken at that time were discarded since they introduced an unintended variable into the study. All future measurements were conducted in an enclosed space, with nitrogen added to reduce the humidity. The container averaged a humidity level of approximately 7%–10%. We now believe that given more time for the wafer to adjust to the low humidity environment, the device lifetime could have improved substantially; a future study is needed to confirm this theory.

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List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
Au	gold
BiCMOS	bipolar junction transistor enabled complimentary metal-oxide-semiconductor technology
CMOS	complementary metal-oxide-semiconductor
FET	field effect transistors
GaAs	gallium arsenide
MEMS	microelectromechanical system
Pt	platinum
PZT	zirconate titanate
R_c	contact resistance
RF	radio frequency
Ru	ruthenium
SiGe	silicon-germanium
Ti	titanim
Vact	actuation voltage
Zr	zirconium

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